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PROTECTION OF NONMETALLIC AIRCRAFT FROM LIGHTNING

I - GENERAL ANALYSIS

High Voltage Laboratory
National Bureau of Standards

NACA

WASHINGTON

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INTRODUCTION

It is the purpose of this report to attempt in a preliminary way to give a logical and consistent analysis of the problem of providing adequate protection to the personnel, contents, and structure of nonmetallic aircraft against the effects of electric shock, mechanical damage, and fire which are almost certain to occur if an unprotected aircraft is struck by lightning. Many of the statements given below are rather obvious to an electrical engineer and are given in rather elementary language but are included for completeness and for the information and orientation of the nonelectrical reader. It is hoped that the analysis will bring out clearly the questions on which further experimental work is needed, and the assumptions which must at present be made to bridge the gaps in our knowledge of the phenomena associated with lightning. The results of future experimental work may perhaps show that other factors must also be considered and that some of the assumptions made herein were not justified.

GENERAL ANALYSIS

The modern problem of the protection of aircraft from lightning has many points both of similarity with and of difference from the corresponding ancient problem of protecting structures on the ground. The basic ideas of Benjamin Franklin are still applicable.. The lightning discharge is substantially the same in both cases, although there is some indication that the crest values of current encountered at high altitudes and presumably in cloud-to-cloud discharges may be less than those measured at the ground (reference 1). This is because of the greater immediate availability of the large charges induced on the conducting ground as contrasted with those stored in the electrically insulating storm cloud.

In both cases, the voltage which forces the lightning discharges through the air is so enormous (of the order of at least 100 million volts and perhaps ten times this value) that there is no possibility of interposing any insulating barrier that can effectively resist it. Hence the remedy is to provide one or more paths for the discharge, so that all except perhaps a tiny fraction of the current will bypass the protected region. Such paths are commonly called "lightning conductors."

The primary difference in the two problems arises from the fact that the weight of the lightning conductor is a matter of extreme importance on aircraft but is quite negligible on ground structures. Also in ground installations it is often possible to avoid effects, such as "side-flash" to personnel, by allowing large clearances between the lightning conductors and the objects protected. In aircraft no space can be spared for such clearances. Protruding rods and screens are taboo because of their aerodynamic drag. Common practice on buildings, monuments, and so forth, is to use very thick metal conductors. The American Standards Association Code for Protection Against Lightning (reference 2) specifies conductors weighing not less than 187.5 pounds per 1000 feet for copper or 320 pounds per 1000 feet for galvanized steel. This has been done partly to provide against corrosion over long periods of time and against mechanical breakage, and partly to obtain, with certainty, a large factor of safety against an unknown possible upper limit of lightning current. Obviously, at least for military aircraft, the system of lightning conductors must be planned with a much less generous factor of safety and with an arrangement of conductors carefully chosen as to material and size and placed strategically so as to give a maximum of protection with a minimum of weight. To the (perhaps limited) extent that conductors already present for other reasons (e.g., control cables or electric wiring) can safely be used as part of the lightning conductor system, a corresponding saving in weight may be gained.

It is evident that the best protective conductor system for each particular design of nonmetallic aircraft must be worked out for the particular dimensions, location of vulnerable contents, arrangement of metallic parts, and other conditions peculiar to that design.

FUNCTIONS OF LIGHTNING CONDUCTOR SYSTEM

The lightning conductors should perform the four following rather distinct functions:

1) They should intercept any direct stroke which may approach the craft and insure that it does not first strike personnel or cargo.

2) They should guide a discharge away from any part of the craft where its blasting or igniting effects would cause damage as (a) in a confined air space or (b) within the thickness of the wooden skin or structural members.

3) They should minimize the tendency for electromagnetic induction to circulate any appreciable fraction of the discharge current through the bodies of personnel, or through other circuits which would be damaged thereby.

4) They should shield the contents of the aircraft electrostatically so as to minimize the tendency to "side flash."

Almost any reasonable arrangement of lightning conductors will have a beneficial effect in all four of these respects, but the four functions are inherently distinct and it is best to consider them separately, as will be done in the following paragraphs.

INTERCEPTION OF STROKE

For effective interception a part of the lightning conductor system must be exposed at all points where a lightning discharge path may enter or leave the aircraft. The skin of an all-metal plane automatically gives an interception which is practically perfect, except for the window openings and radio antennas. A completely nonconductive aircraft might conceivably be struck almost anywhere. Practically, however, the presence of control cables and wiring, and of rain water on the outer surfaces will markedly concentrate the electric field at projecting extremities of the craft and greatly increase the probability of a stroke hitting these portions, while the chance of strokes to the central parts and to re-entrant angles is correspondingly reduced. Returns from the NACA questionnaire indicate that with metal aircraft a high percent of observed stroke damage involved two extremities (wingtips, nose or tail) and only very few occurred at less exposed areas.

Unfortunately very little is known about the factors which influence in detail the path of a lightning stroke. In general, the stroke is in the direction of the electric field between clouds or from cloud to ground. However a comparison of the smooth, nearly parallel lines of force as drawn in text books on electrostatics with the crinkled, tortuous and often branched path of an actual spark makes it evident that other conditions influence the details of the path. Perhaps the developing streamer in the pilot leader stroke is affected by the presence near its tip of available ions and particularly of electrons freshly released either by cosmic radiation, or by the St. Elmo's Fire, or corona discharge, which often precedes lightning strokes to aircraft. If this latter effect is of importance it constitutes further reason for the concentration of discharges near the extremities.

The classical mathematical approach to problems of electrical screening is the solution by Maxwell (reference 3) of the problem of the electric field on the two sides of a row of parallel charged wires. However, this method of treatment is applicable only when the distance of the protected object behind the screen is somewhat greater than the spacing between wires. In aircraft the protected objects must be fairly close to the screening wires and the resulting shielding effect can be calculated only in those cases where the screen is of fine mesh.

In view of this situation it appears that about the only basis for judging the merits of a given arrangement of lightning conductors as regards the function of interception is be experimental trails. Such trials are subject to several limitations. If made on full-size aircraft, the limited voltage available artificially requires that tho electrode representing the charged cloud must be fairly close (6 to 8 ft) to the place struck so that conditions are quite different from those in nature. If experiments are made on modols, the natural proportions of stroke length to model size can be approximated; but the question arises as to whether the model can duplicate minor features such as sharpness of points, and so forth, which may be significant. Also the stopped character of the leader stroke, discovered by

Schonland (reference 4), implies that the structure of a streamer is such that lengths of something like 150 feet are a significant feature of the mechanism of natural lightning and such a distance cannot be duplicated in a model experiment.

Another consideration arises from the fact that in nature the potential gradient builds up relatively slowly, so that there is ample time for corona to develop before the final discharge occurs. This suggests that the experiments should preferably be made with direct current. Unfortunately, extremely high direct-current voltage is not so generally available as surge voltages. Presumably experiments should be tried with both and perhaps with 60-cycle alternating-current also.

A further complication may arise by reason of the rapid motion of the aircraft relative to the air. This produces a tendency for the ionized path to blow back toward the trailing edges of the wings and toward the tail of the craft, after the initial discharge has occurred. This effect doubtless accounts for the burns occasionally found along the belly of an aircraft. It is less certain, however, that the air velocity affects the initial point of contact, because the velocity of streamer development (never less than 100 km per sec) is far greater than that of the aircraft (0.1 km per sec).

GUIDING OF STROKE

If the tip of the lightning discharge streamer strikes a metallic conductor which leads in the general direction of the electric field, the lightning current will flow in the conductor and be guided by it. An exception to this arises if the conductor is bent to such an extent that the inductive voltage $L\,dI/dt$ in any portion of the conductor is greater than the sparking voltage between the ends of that portion. Then a spark will occur through the air, or other insulating material, and the current will bypass the conducting loop.

If the discharge first encounters an insulating material (e.g., plywood), any of several things may happen.

1) The discharge may continue as an arc in the air close to the outside surface of the plywood until it reaches a conductor. In this case a considerable momentary rise in air pressure (blast effect) and local scorching may occur which may or may not cause appreciable damage.

2) The discharge may puncture the insulator and pass inside the structure (wing, or control element) to the nearest conductor. In this case there may be a similar blast effect but in the other direction. If the space inside is confined to a fairly small volume, the energy liberated by the discharge may develop enough air pressure to blow off the coverings. A rough calculation indicates that the energy per unit length in a powerful lightning stroke if distributed throughout a space 3 meters in diameter around its path would multiply the absolute temperature and hence the pressure (at constant volume) by a factor of 10.

Also if any explosive vapors (as from spilled gasoline) are present they may explode.

3) The discharge may pass in the grain of one of the layers of the plywood, presumably because it contains residual moisture and hence a slight conductivity. In this case there is usually a very marked explosive action (probably because of the formation of steam in the grain of the wood) and the plywood is badly shattered for some inches each side of the discharge path. Probably if the material were sufficiently insulating and free from moisture, as the result of very thorough impregnation, this third case would not occur and the discharge would prefer an air path on one side or the other of the insulating panel. However, the experimental panels submitted by the Bristol Aeronautical Corp., which were presumably made with at least the usual care, showed bad shattering. Hence it is doubtful if present manufacturing methods can be expected to produce a plywood structure which would be free from this hazard and would remain so after exposure to weather for any considerable period of time.

It has been demonstrated that a guiding action, sufficient to keep the discharge in the air outside of a plywood panel, can be furnished by a strip 1 centimeter wide of conducting paint, which may have a resistance of 2500 ohms per centimeter. Even aluminum paint which has nearly infinite resistance if measured at low voltages, but which contains conducting particles, the gaps between which can be bridged by sparks at higher voltage gradients, also exerts a marked guiding action. These effects may be of use in protecting the smaller control surfaces and in bonding otherwise insulated metal parts.

ELECTROMAGNETIC INDUCTION EFFECTS

The current in a lightning discharge consists of one or several intense, unidirectional pulses of short duration, between and following which there may be a more or less steady flow of electricity at a much lower rate. The wave front, though very steep, has been found experimentally to last for about 1 microsecond and hence, since it propagates along a metallic conductor with the velocity of light, to extend longitudinally 1000 feet. Hence it is permissible to consider that at any instant the current has substantially the same value at all points along the length of any path between the extremities of the aircraft. Because of the very high rates of increase (and of decrease) in the current, the effect of even a small inductance in the circuit is much more important than that of considerable resistance. A lightning conductor may have an effective self-inductance of only 10^{-8} henries for each centimeter of length but the current may well increase by 10,000 amperes in a millionth of a second. The rate is then 10^{10} amperes per second and the induced voltage drop is 100 volts per centimeter or 3,000 volts per foot. The resistance drop in no. 10 copper wire at 10,000 amperes would be only 10 volts per foot. If the body of an occupant of the aircraft should in effect span any considerable length of the lightning conductor, the voltage tending to send current through his body might well be several thousand volts, but will be far less than the full voltage which initiates the lightning stroke. There is therefore a possibility that sufficient insulation can be provided to resist puncture by this induced voltage and thus to prevent any diversion of current through the personnel. In the absence of insulation, the current will be approximately equal to the gradient of the induced voltage divided by the impedance of the branch path. The resistance of the human body to direct current is usually at least 200 ohms and a sustained current of 0.01 ampere is not fatal, though quite unpleasant. Hence a direct voltage of 20 volts is quite harmless. For the rapidly changing voltage of a lightning surge the human skin may offer appreciably less impedance but on the other hand it is probable that, for the very short time intervals involved here, the human nervous system can endure considerably greater currents than the value quoted above. It is planned to study this question experimentally later in this work.

At least 300 volts is required to produce even a very short jump spark in air at normal density. Moderate insulation by clothing, gloves, or shoes will further raise the voltage which it is permissible to induce in any possible circuit through a person's body. The solution of this part of the problem is therefore to provide sufficient conducting paths so located as to keep the induced voltage down to a moderate value and to insulate against this voltage. The use of electrically heated clothing, headphones, and other electrical equipment greatly complicates this problem.

The way in which such induced voltage effects can be analyzed is indicated in figure 1. At (a) the line AB indicates the lightning conductor in which the current is flowing, while conductor CD represents a control cable. The induced voltage can be calculated from the magnetic field which links the rectangle CDFE, in other words, from the self inductance of EF "with return at CD." If the induced voltage exceeds the sparking voltage of the gaps at E and F, these will break down and part (roughly half) of the current will flow through CD. Substantially the same voltage would be induced in the separate circuit CDF'E', shown in figure 1 (b) provided E'F' were very close to EF. This latter voltage may be calculated from the mutual inductance between the secondary loop CDF'E' the primary circuit formed by the conductor AB and the lightning channel, the return current in the primary being the displacement current in the surrounding air which results from the removal of the cloud charge. The effectiveness of an arrangement of shielding conductors is thus expressible in terms of a mutual inductance M. If the induced voltage is to be kept below the minimum value which will produce a jump spark - namely, about 300 volts - the value of M should not exceed 3×10^{-8} henries for the worst case likely to arise. This case would be one in which the distance EF spanned the full length of the fuselage or wing, the distance CE was the full width, and the separation between EF and E'F' was a minimum. For a length of 30 feet, width 4 feet, and separation between EF and E'F' of 1 inch $M = 710 \times 10^{-8}$. Hence some modification of the single conducting wire is needed which will reduce M by a factor of about 250.

If a second conductor such as GH in figure 1(c) is provided, there is a reduction in M, first because the division of current leaves only half of the original current in AB and, second, because the magnetic field produced at points in the plane of the loop by the current in GH is opposite in direction to that produced by the current in AB, and tends to neutralize its effects. In fact, if the loop is located symmetrically between the two conductors the neutralization will be perfect and M will be zero. If the loop is much closer to one conductor than to the other the neutralization will be correspondingly incomplete. As still other paths are added in parallel between the ends of the fuselage, the neutralization becomes more perfect. In the particular case in which the fuselage is a circular conducting tube with the discharge current distributed uniformly around its periphery (fig. 1(d)); the neutralization is perfect, and M is zero, for any location of the secondary loop inside the tube.

Instead of considering the voltage induced in a rectangular secondary loop, we can imagine (fig. 1(e)) a conductor JEFK passing along the axis of the fuselage. If this conductor is cut between E and F the induced voltage measured at the cut will be that induced in a secondary circuit which consists of the series connection of (1) the conductor EJ, (2) the two conductors JGHK and JABK in parallel and (3) the conductor KF. Such a secondary circuit represents almost the worst possible, from the present point of view, and if the voltage induced in it can be kept down to a safe value, any other internal loop will be still safer. The induced voltage has been computed for this simple case and for cases in which several straight shielding conductors (arranged at a distance of 1 m from the central conductor) are present. The computed values are given in table I and include values of self and mutual inductance per centimeter as well as of induced voltage per foot. These computations are based on the assumption that the primary conductors are long in comparison with their cross sections and spacing, that the current divides equally among them, and that the current is changing at the rate of 10^{10} amperes per second.

Each column in table I corresponds to a different possible arrangement of conductors, as described in row 1. Rows 5 and 6 show, respectively, the total external voltage drop per foot which would exist across the ends of a structure while current is building up at the rate of 10^{10} amperes per second. This is the voltage that would be measured by a voltmeter, the loads of which were attached to points one foot apart and extended away perpendicular to the axis to a very great distance before coming together at the voltmeter. The values in row 6 are based on the effective return circuit of the lightning current being at an average distance of one kilometer from the aircraft - that is, about half the radius of a cloud. Those in row 5 are based on a return circuit at 100 meters, this being a more reasonable estimate of the distance to which the magnetic field could have time to propagate in the short time allowed by a steep wave front. It will be seen that the difference between the values in the two rows is of minor significance, so that a more precise definition of the return circuit is unnecessary. It also appears that the addition of parallel conducting paths does not reduce the <u>external</u> voltage drop by a very large factor.

The values in row 7, on the other hand, give the <u>internal</u> induced voltage - that is, that which would be measured by a voltmeter connected at EF of figure 1(c). It will be seen that these values are materially less than the external voltage and that the use of a plurality of conducting paths and of wide conducting paths can result in a material reduction in the voltage. Barring some improper arrangement of control cables or wiring, it is unlikely that an individual would span more than 6 feet of circuit and he would then be exposed to the voltages listed in row 8. While it would be difficult to insulate against 25,000 volts, it is relatively easy to protect against surges of 1800 volts.

The merits of a given arrangement of lightning conductors as regards their reductions of electromagnetic induction effect can be expressed by stating the mutual inductance M between the lightning current path and any path through personnel or other vulnerable contents. The procedure for measuring this M, which it is proposed to try first, is to send a surge current, of moderate value I, but of fairly steep wave front, so that dI/dt is of the order of 10^{10} amperes per second. (This value is about the median observed in natural lightning (reference 5) through the aircraft between any desired pairs of extremities and to measure the crest voltage E induced between various conducting bodies - wiring, dummy personnel, control cables, communication apparatus, and so forth, within the craft.) The ratio of E to dI/dt is the value of M. It is possible that bridge methods using sustained audio-frequency may also prove useful for this purpose. It is also possible to calculate values of M for cases in which the conductor in question approximates simple geometrical shapes, as in table I.

"SIDE-FLASH"

In lightning strokes to buildings a commonly observed occurrence is the passage of a visible spark from the main discharge path to isolated conducting objects: for example, stoves, metal bedsteads, and so forth. Such effects are called "side-flash." If they should occur in an aircraft, there would be a hazard (1) of igniting any gasoline vapor which might have accumulated and (2) of an uncomfortable and perhaps serious electric shock to personnel.

The tendency for such "side-flashes" to occur can be expressed in a quantitative manner, as follows: Prior to the stroke, the aircraft and its contents are all at the same electric potential which has some value intermediate between that of the thundercloud and that of the earth. The first stages of the stroke serve suddenly to change the lightning conductors to a new potential which may differ from its previous value by some hundreds of millions of volts. Electrostatic induction by reason of the direct capacitance, C_{pc} between the pilot and the lightning conductor will tend to change his potential also, but the direct capacitance, C_{pg} from the pilot to ground and to distant regions will prevent this shift in potential from being complete. Hence, there will exist momentarily between any conducting body, such as the pilot, gasoline tank, or other internal object, and the lightning conductor system a difference of potential ΔV given by the relation:

$$\Delta V = \frac{V_o\, C_{pg}}{(C_{pc} + C_{pg})}$$

Here V_o is the change in potential of the lightning conductor due to the stroke and may be of the order of 10^8 volts. If ΔV is to be kept down to a few hundred volts, the ratio $\frac{C_{pg}}{C_{pc}}$ should be as small as 10^{-6}. With a lightning conductor, which consists of only a single wire, $\frac{C_{pg}}{(C_{pc} + C_{pg})}$ is much too high. With the addition of more conductors around the protected object, C_{pc} will increase slightly and C_{pg} will decrease rather rapidly.

If the metal of the plane completely surrounds the contents, C_{pg} becomes strictly zero and so does ΔV. This desirable condition obtains in an all-metal aircraft except for the effect of the windshield openings.

If the distance between the internal object and the lightning conductor is too short, the voltage difference ΔV will produce a "side-flash" spark between them. The amount of charge q transferred by this spark is given by the product $q = C_{pc} \Delta V$ (or by $C_{pg} V_o$). A reasonable estimate for C_{pc} is 10^{-10} farads and if ΔV is only 10,000 volts, the charge will be only one microcoulomb. Such a spark is very different from that caused by electromagnetic induction and would perhaps not give a serious shock to personnel but would be sufficient to ignite an explosive vapor mixture. If the internal object is connected electrically to the lightning conductor, there will be no spark, but still a charge q will pass through the connector. If the connection is by way of a man's arm or leg a corresponding shock will be felt.

Such "side-flash" sparks will tend to occur to any small insulated metal parts (aileron hinges, brackets, etc.). If it should be found that the current in such sparks is enough to damage the plywood structure, the parts should be bonded to the conductor system, perhaps by conducting paint.

It will be noted that a "side-flash" spark caused by electrostatic action does not, in general, carry any considerable part of the main discharge current. Hence it is not nearly as dangerous as the spark resulting from electromagnetic induction, although the voltage causing it may be materially higher. An interesting question which arises is: Can a "side-flash" spark set up a conducting path through which electromagnetic induction will thereupon divert a dangerous fraction of the main current? Under most circumstances the answer is "no," but such an effect seems possible in the particular circumstances shown in figure 1(f). Here a control cable CD is separated from the system of lightning conductors AB by two spark gaps. Gap G_1 is assumed to have electrodes with smoothly rounded surfaces which will permit a spark to develop very quickly if sufficient voltage is applied, but this gap is assumed to be so wide that the maximum voltage induced by electromagnetic action is not enough to jump it. Gap G_2, on the other hand, is assumed to have sharply pointed elecrodes and hence to exhibit a time lag in the production of a spark, but it is also assumed to be short enough to be jumped by the electromagnetic voltage. When such a structure is subjected to a lightning discharge the high "side-flash" voltage may be enough to jump G_1 and will do so before G_2 has time to break down. The full electromagnetic voltage then will be impressed on C_s, which may break down a little later and thus permit a goodly fraction of the main current to pass through CD.

The determination of the merits of a protective structure as regards "side-flash" requires a determination of the capacitance ratio $\frac{C_{pg}}{C_{pc}}$. To compute these values from the size and shape of the conductors is impracticable. It is perhaps possible to measure them with an audio-frequency bridge but the very small value of C_{pg} makes it probable that the effect of the stray capacitance of leads would make such a measurement exceedingly difficult. It is therefore proposed to determine the ratio by supporting the aircraft under test on insulators and changing it suddenly to a considerable potential V_0 by a surge generator. An electronic crest voltmeter, with capacitance coupling, connected between the lightning conductor and the test object (e.g., a dummy pilot) measures ΔV and the quotient of those voltages should give the desired ratio.

National Bureau of Standards,
Washington, D. C., March 3, 1943.

REFERENCES

1. Robertson, L. M., Lewis, W. W., and Foust, C. M.: Lightning Investigation at High Altitudes in Colorado. Elec. Eng., vol. 61, April 1942, p. 204.

2. Anon.: Code for Protection Against Lightning. Nat. Bur. Stds. Handbook H 21, 1937, p. 14.

3. Maxwell, J. C.: Treatise on Electricity and Magnetism. 3d. ed., vol. I, par. 203, p. 310.

4. Schonland, B. F. J.: Proc. Roy. Soc., A. vol. 164, 1938, p. 132.

5. Wagner and McCann: Elec. Eng., October 1941, p. 499.

TABLE 1.- VOLTAGES INDUCED IN VARIOUS STRUCTURE BY ELECTROMAGNETIC INDUCTION

Row	Case	I	II	III	IV	V	VI	VII	VIII	IX
1	Structure	1 no. 10 wire	1 6 in. strip	2 no. 10 wires	2 6 in. strips	4 no. 10 wires	4 6 in. strips	8 no. 10 wires	8 6 in. strips	Complete cylinder diameter = 2m
2	Self inductance per cm, abh $R = 10^4$ cm	23.0	16.0	15.4	12.0	12.0	10.2	10.4	9.6	9.2
3	Self inductance per cm, abh $R = 10^8$ cm	27.6	20.6	20.0	16.6	16.6	14.8	15.0	14.2	13.8
4	Mutual inductance per cm, abh	13.8	6.8	6.2	2.8	2.8	1.0	1.2	0.4	0
5	Inductive volts per ft, external $R = 10^4$ cm	7,000	4,900	4,700	3700	3700	3100	3200	2900	2800
6	Inductive volts per ft, external $R = 10^8$ cm	8,400	6,300	6,100	5100	5100	4500	4600	4300	4200
7	Inductive volts per ft, internal	4,200	2,100	1,900	850	850	300	370	120	0
8	Internal volts on 6 ft span	25,000	13,000	11,000	5100	5100	1800	2200	720	0

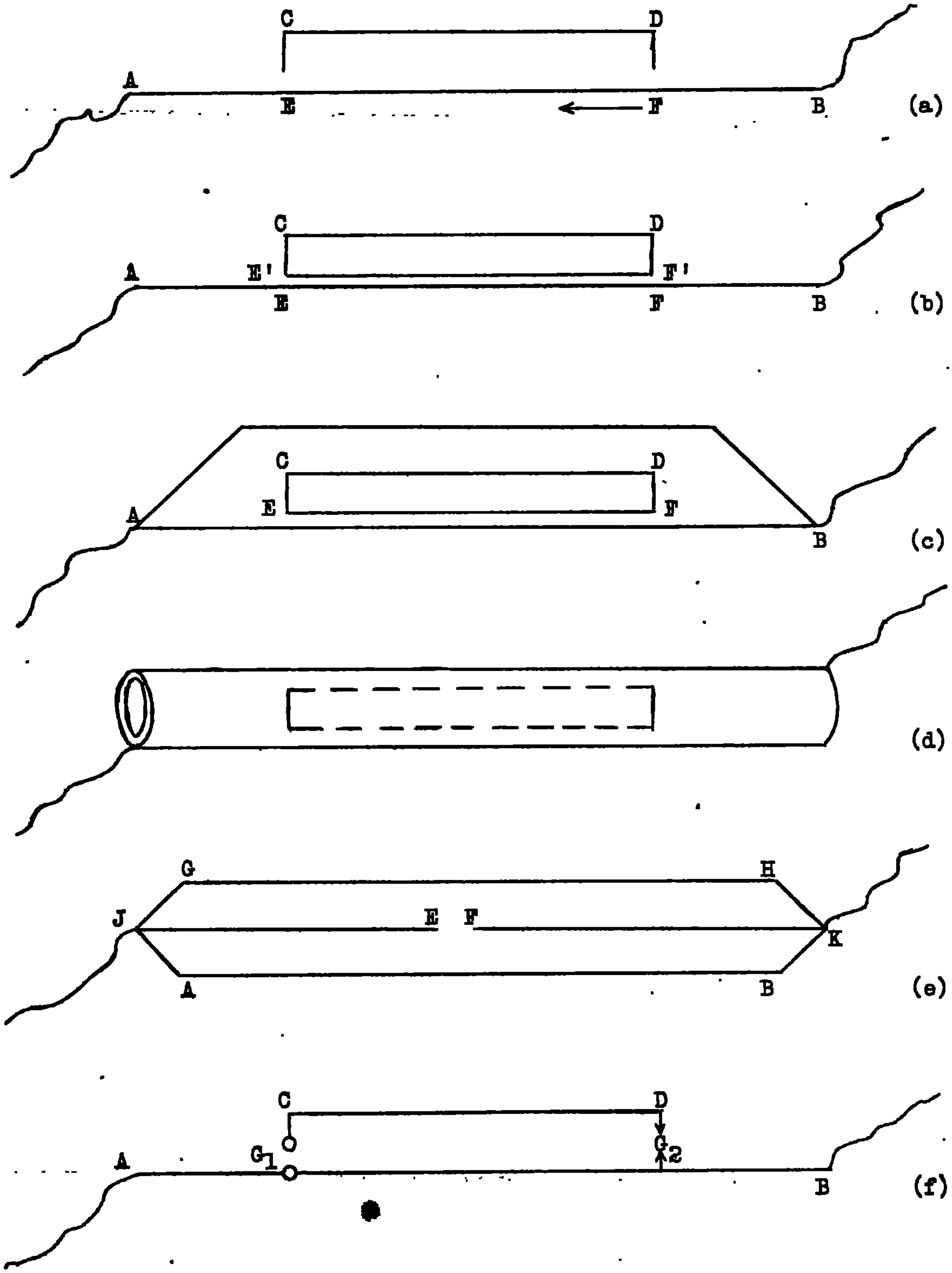

Figure 1.